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Photonic Microwave Filter employing an Opto-VLSI-Based Adaptive Optical Combiner

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Abstract—**A reconfigurable photonic microwave filter structure employing an Opto-VLSI based adaptive optical combiner is proposed and experimentally demonstrated. The Opto-VLSI based adaptive optical combiner is used to combine RF modulated optical signals with a user-defined weight profile to realize a reconfigurable RF photonic filter response. Theoretical simulations are in excellent agreement with the experimental results that demonstrate the concept of the photonic microwave filter structure.**

Index Terms— **Microwave photonics, optical processing of microwave signal, liquid crystal devices, photonic microwave filters, opto-VLSI processor.**

I. INTRODUCTION

THE processing of radio frequency (RF) and microwave signals in the optical domain is an attractive approach to overcome the bottlenecks of bandwidth, power loss, and electromagnetic interference (EMI) encountered in conventional electronic signal processing systems [1-4]. A wide range of emerging RF signal processing applications require specifically high resolution, ultra-wide bandwidth, wide-range tunability, and fast reconfigurability. While these requirements are difficult to achieve using conventional all-electronic processing, they are feasible with photonics-based signal processing [5, 6].

Photonics-based RF signal processing can potentially provide advantages including (i) high resolution broadband delay lines (transversal filters) through the use of Fibre Bragg Gratings (FBGs) or dispersion optical fibres (ii) adaptive filtering of RF signals (iii) fast sampling of RF signals (iv) suppression of optical carriers and sidebands (v) optical beam steering and splitting (vi) optical coding for secure communications [7, 8]. Their small size, low weight and low power attenuation make optical fibres excellent candidates for realising delay lines for the synthesis of digital impulse response RF filters in the optical domain.

By modulating an optical carrier by an RF signal and then split the resulting RF-modulated optical signal by a power splitter, one can generate a large number of taps. By using optical fibre delay lines having a constant differential delay, T, and then recombining and detecting the combined optical signals using a photodetector, a transversal RF filter is realised. The ability to dynamically recombine the delayed RF-modulated optical signals with arbitrary weights has the potential to realise an adaptive transversal RF filter, whose resolution depends on the tap counts and the minimum attainable delay [1-3].

The use of optical combiners in conjunction with variable optical attenuators is one of the potential approaches used to synthesise a transversal RF filter response with variable weights [9-11]. However, for a high order transversal filter the implementation and control a large number of variable optical attenuators become impractical.

In this paper, we propose and experimentally demonstrate the concept of a new Photonic microwave filter employing an Opto-VLSI-based adaptive optical signal combiner. A single Opto-VLSI processor can be reconfigured in real time, allowing a large number of RF-modulated optical signals to be dynamically attenuated, thus making adaptive photonic RF signal processing practical [5, 12]. The demonstrated photonic microwave filter can be reconfigured via software, thereby synthesizing the weights of the filter taps by uploading multicasting phase hologram onto the Opto-VLSI processor.

II. OPTO-VLSI BASED ADAPTIVE OPTICAL COMBINER

An Opto-VLSI processor is a reconfigurable diffractive optical element capable of steering/shaping an incident optical beam electronically without mechanically moving parts. As shown in Fig. 1, an Opto-VLSI processor comprises an array of liquid crystal (LC) cells driven by a Very-Large-Scale-Integrated (VLSI) circuit [13, 14], which generates digital holographic diffraction gratings that achieve arbitrary beam deflection/multicasting. A transparent Indium-Tin Oxide (ITO) layer is used as the second electrode, and a quarter-wave-plate (QWP) layer is deposited between the LC and the aluminum mirror to accomplish polarization-insensitive operation. The voltage level for each pixel can individually be controlled by using a few memory elements that select a discrete voltage level and apply it, through the electrodes, across the LC cell.

A multicasting phase hologram uploaded onto an Opto-VLSI processor can either split and optical signal into N output signals with arbitrary power attenuation [13], or combine *N* input incident optical beams into a single output beam with each input beam being arbitrarily attenuated. Several computer algorithms, such as the genetic, simulated annealing, phase encoding, and projection algorithms have been used for generating optimized multicasting phase holograms that produce a target splitting or combining profile [15].

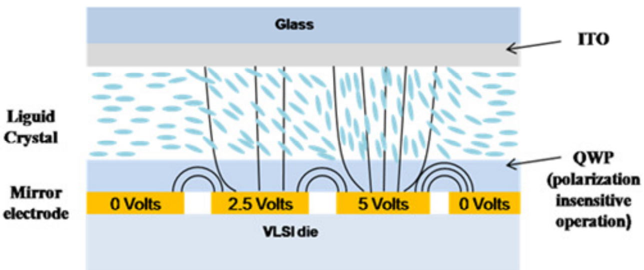

Fig. 1. Opto-VLSI processor layout, Opto-VLSI cell structure and pixel architecture.

The structure of the adaptive optical signal combiner is shown in Fig. 2. It consists of an Opto-VLSI processor, a lens, and an optical fiber array, aligned to form a 4-f imaging system. The Opto-VLSI processor has 1×4096 pixels with pixel size of 1.0 µm wide and 6.0 mm length, and 1.8µm pixel pitch (i.e. 0.8 µm of dead space between pixels). To demonstrate the 1×4 adaptive optical combiner, a custom-made fiber array with spacing 127 µm was used. The spacing between the inputs ports was 254 µm (twice of the fiber array spacing), thus the inputs beam angles were θ= ±0.58, ±1.16 with respect to the output beam direction, as illustrated in Fig. 2. A lens of focal length f = 25 mm was placed between and at an equal distance, f, from both the fiber array and the Opto-VLSI processor. Four optical signals of equal power levels (-5.7dBm) were launched into Ports 1, 2, 3 and 4 as illustrated in Fig. 2, and, through a multicasting phase hologram, combined into Port 5, which was monitored using an optical spectrum analyzer. A multicasting phase hologram uploaded onto the Opto-VLSI processor enabled the four optical signals launched into Ports 1-4 to be combined at Port 5 with a weight profile that matches the combining profile of the corresponding multicasting phase hologram.

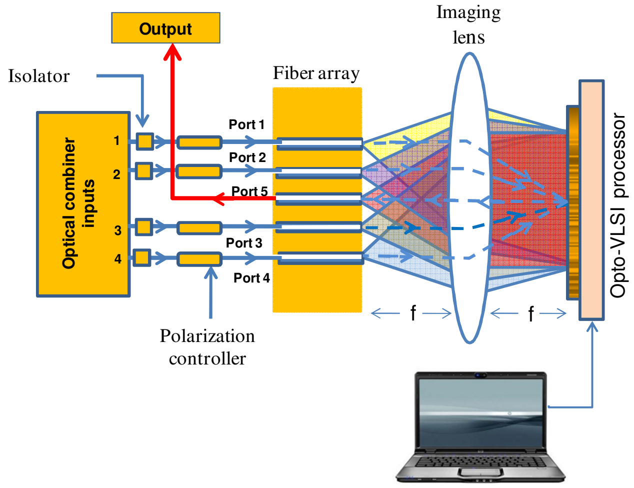

Fig. 2. Opto-VLSI based adaptive optical signals combiner structure.

III. PROPOSED PHOTONIC MICROWAVE FILTER

The proposed photonic microwave filter is illustrated, through an experimental setup, in Fig. 3. Four laser sources of similar output power and a wavelength separation of Δλ, were launched into the Opto-VLSI-based adaptive optical signal combiner (described in Fig. 2). The output combined optical signal was amplified by an erbium-doped fiber amplifier (EDFA). The amplified optical signal was externally modulated by an RF signal through an electro-optic modulator (EOM). The wavelength division multiplexed (WDM) modulated light was launched into a high dispersion fiber (HDF), which has a dispersion coefficient of 382.5 ps/nm and insertion loss of 4.6 dB. Each WDM channel experienced an RF delay that depends on its centre wavelength. After photodetection, the generated output RF signal is the sum of delayed versions of the input RF signal, whose weights depend on the combination profile set by the Opto-VLSI processor. Therefore, the structure shown in Fig. 3 represents a photonic microwave filter, whose response can be tuned by the Opto-VLSI processor. A lightwave component analyser was used to generate the input RF signal and read out the filter response expressed as [7]

$$H(f) = \sum_{r}^{M} a_r \exp[-j2\pi r f \tau] \qquad (1)$$

where f is the RF frequency, M is the number of the detected RF-modulated wavebands, a_r is the r th tap weight, which is proportional to the optical power of the

r th waveband, and τ is the time delay between adjacent wavebands introduced by the HDF. The time delay τ can also be expressed in terms of the dispersion of the HDF as

$$\tau = \alpha \cdot \lambda \qquad (2)$$

where α denotes the dispersion coefficient of the HDF, and $\Delta\lambda$ is the adjacent waveband separation.

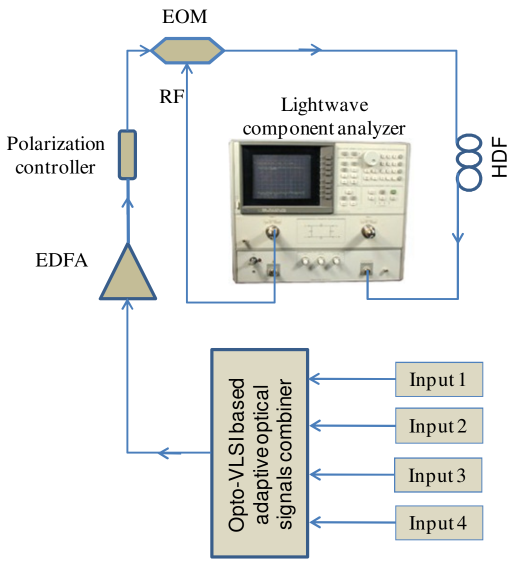

Fig. 3.Schematic diagram of the proposed photonic microwave filter employing an Opto-VLIS based adaptive optical signal combiner.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Several weight profiles were synthesized, using 4 WDM channels, and uploaded onto the Opto-VLSI processor to demonstrate the principle of the proposed photonic microwave filter experimentally.

Figs 4(a), (c), and (e) show the weight profiles of the four WDM channels, spaced at Δλ =1nm center-to-center, corresponding to combining profiles of [1, 1, 1, 1], [0.6, 1.0, 1.0, 0.6], and [0.5, 1.0, 0.8, 0.5], respectively. Figs 4(b), (d) and (f) show the corresponding measured and simulated RF responses. Excellent agreement between the measured and simulated RF responses is seen at low frequencies. The discrepancies at high frequencies are attributed to the limited bandwidth (4 GHz) of the EOM used in the experiments.

Figs 5(a), (c), and (e) show the weight profiles corresponding to combining profile equal to [1, 1, 1, 1], [0.6, 1.0, 1.0, 0.6], and [0.5, 1.0, 0.8, 0.5], respectively, when the WDM channel spacing was increased to Δλ =2nm center-to-center. Figs 5(b), (d) and (f) show the corresponding measured and simulated RF responses. Note that, by changing the WDM weights while keeping a constant WDM channel spacing, the center frequency of the filter is kept unchanged, while the filter's rejection is changed. By increasing the WDM channel spacing, a narrower pass band is synthesized.

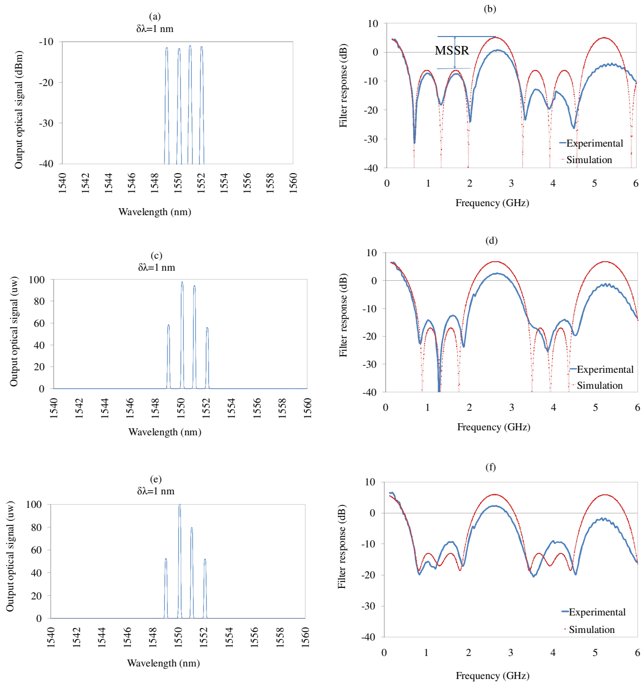

Fig. 4. (a), (c) and (e) Weight profiles of the four WDM RF-modulated channels and (b), (d) and (f) corresponding RF filter responses. Weight profile in (a) is [1, 1, 1, 1], in (c) is [0.6, 1.0, 1.0, 0.6], and in (e) [0.5, 1.0, 0.8, 0.5]. WDM channel spacing is 1nm centre-to- centre.

The theoretical Main Lobe to Sidelobe Suppression Ratio (MSSR) for uniform tap filter is around 13 dB which is in excellent agreement with the experimental results. The MSSR value was increased up to 20dB when the weight profile was changed from [1, 1, 1, 1], to [0.6, 1.0, 1.0, 0.6] as evident from Fig. 4(d) and Fig. 5(d).

The ability of the Opto-VLSI processor to control the MSSR value and the pass band of the microwave filter through the synthesis of optimized combination weight profile demonstrates the principle of the proposed photonic microwave filter.

V. CONCLUSION

A novel structure of photonic microwave filter that employ an Opto-VLSI based adaptive optical combiner has been proposed and experimentally demonstrated. Different weight profiles have been generated, demonstrating the ability of the Opto-VLSI based adaptive optical combiner to dynamically combine multiple input optical signals with user-defined weight profiles, thus realising a tunable microwave filter.

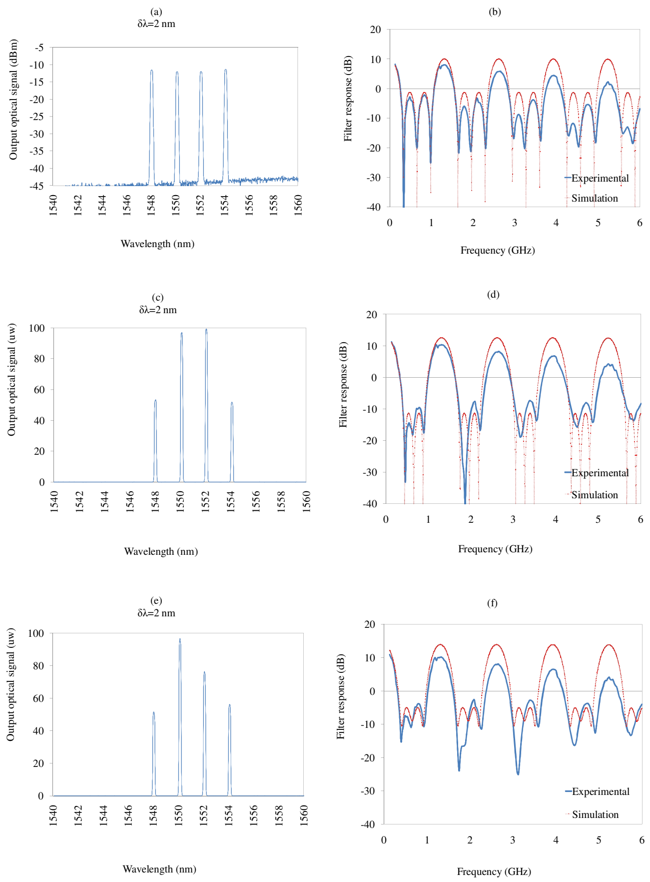

Fig. 5. (a), (c) and (e) Weight profiles of the four WDM RF-modulated channels and (b), (d) and (f) corresponding RF filter responses. Weight profile in (a) is [1, 1, 1, 1], in (c) is [0.6, 1.0, 1.0, 0.6], and in (e) [0.5, 1.0, 0.8, 0.5]. WDM channel spacing is 2nm centre-to-centre.

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